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To cite this article: N A Abaimov *et al* 2016 *J. Phys.: Conf. Ser.* **754** 112001

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# Experimental and computational study and development of the bituminous coal entrained-flow air-blown gasifier for IGCC

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**Abstract.** In the paper the development of the advanced bituminous coal entrained-flow air-blown gasifier for the high power integrated gasification combined cycle is considered. The computational fluid dynamics technique is used as the basic development tool. The experiment on the pressurized entrained-flow gasifier was performed by “NPO CKTI” JSC for the thermochemical processes submodel verification. The kinetic constants for Kuznetsk bituminous coal (flame coal), obtained by thermal gravimetric analysis method, are used in the model. The calculation results obtained by the CFD model are in satisfactory agreements with experimental data. On the basis of the verified model the advanced gasifier structure was suggested which permits to increase the hydrogen content in the synthesis gas and consequently to improve the gas turbine efficiency. In order to meet the specified requirements vapor is added on the second stage of MHI type gasifier and heat necessary for air gasification is compensated by supplemental heating of the blasting air.

## 1. Introduction

The coal-fired power industry is widely spread all over the world due to the solid fuels cheapness and availability. The integrated gasification combined cycle units (IGCC) are the most advanced units among the known technologies of solid fuel use [1]. The near zero values of the atmospheric emission of pollutants along with the relatively high electrical efficiency (up to 50-55%) are its basic advantages [2]. As opposed to traditional thermal power plants where coal is burned in steam generation boiler, in IGCC coal is transformed in synthesis gas in the gasifier, the synthesis gas in its turn is a fuel for combustion chamber of the gas turbine unit (GTU). Thus the IGCC operation parameters are generally defined by the solid fuel gasification mode. The basic requirements imposed to the entrained-flow IGCC gasifier are as follows:

- 1) high efficiency (including cold gas efficiency);
- 2) elevated carbon conversion rate;
- 3) minimum pollutant formation rate;
- 4) operational reliability;
- 5) generation of the synthesis gas with composition required for GTU high performance operation.

For development of the gasifier which would completely meet the requirements mentioned above it is necessary to carry out the integrated studies, during which the following items should be analyzed:

- 1) fuel composition, including its kinetic characteristics and ash properties (composition, melting temperature, viscosity etc.);



2) thermochemical processes (TCP) occurring in the gasifier, that is coal drying, pyrolysis, heterogeneous reactions;

3) aerodynamics of the gasifiers interior space;

4) impact of the feeding staged organization on the gasifier operation parameters;

5) features of the unit walls slagging during operation on the project fuel.

The investigation of the fuel properties can be performed by several methods: pressurized drop tube furnace, fluidized-bed process, thermal gravimetric analysis (TGA) etc. The present methods permit to define some TCP regularities but due to the differences in laboratory and industrial units' conditions the actual TCP nature can be understood only by means of studies conducted on the pilot and near-commercial gasifiers. However the measurements' conducting in the entrained-flow gasifiers is rather difficult due to the design features, high pressure (up to 3 MPa) and high temperature (up to 1700°C) in the gasification chambers. Therefore in recent times the physical experimental studies are often combined with the mathematical modeling methods, in particular the Computational Fluid Dynamics (CFD) method which is the most effective one [3]. The entrained-flow gasification models created by means of CFD method consist of several submodels: TCP, turbulence, radiation, convection, dispersed phase motion, slagging etc.

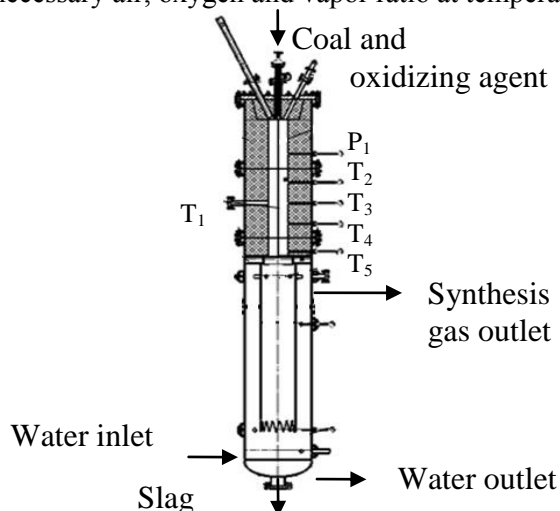
In order to provide the modeling data adequacy all submodels should be verified by means of the experimental data. The TCP submodel is the most important one and at the same time it is the least proven submodel [4]. During the TCP submodels creation and adjustment it is required to use the data obtained at the laboratory and industrial units.

## 2. Experiment description

The entrained-flow pressurized gasifier designed by "NPO CKTI" JSC was used for the TCP submodel verification and validation through the experimental elaboration of the pulverized coal fuel gasification technology.

### 2.1. Gasifier design

The vertical down-flow gasifier consists of two chambers: gasification and cooling chambers (figure 1). The gasification chamber with internal diameter of 0.21 m and height of 1.6 m is located in the upper part. The cooling chamber comprising the water quenching section and the slag bath is located below. The double fuel burner is equipped by the swirl-type and uniflow atomizer in case of operation on the air blast and oxygen blast respectively. There is a possibility of the blast supply with necessary air, oxygen and vapor ratio at temperature within the range of 350-550°C.



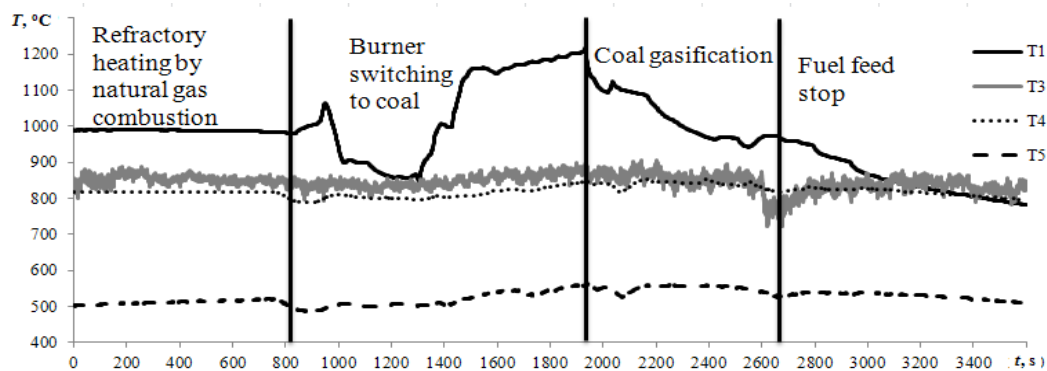
**Figure 1.** Single stage gasifier designed by CKTI.

The unit is equipped by minimum number of the temperature, pressure and flow sensors required for gasification process analysis. The refractory temperature is controlled throughout the height by

means of five platinum platinum-rhodium thermocouples  $T_2$ - $T_5$ , the flow temperature  $T_1$  and the chamber pressure  $P_1$  are also controlled. The synthesis gas composition ( $\text{CO}$ ,  $\text{CH}_4$ ,  $\text{H}_2$ ,  $\text{O}_2$ ) is defined at the gas chromatograph.

## 2.2. Experiment technique

The operation parameters values vary with time in one of the operation modes during experiment. The synthesis gas composition determination method by means of chromatograph assumes that the probe sampling is performed at a given instant therefore it is important to know the basic parameters of the mode in present time. The primary experimental data permits to provide it even in nonstationary conditions of unit operation. The thermal energy necessary for endothermic reactions in the gasifier is supplied to coal as a result of its partial combustion and also from the fire-resistant insulation walls. The high temperature flame core is generally located in the first half of the gasification chamber near the burner; therefore the brickwork temperature possesses the maximum values (figure 2).



**Figure 2.** Temperature history,  $T_1$  is the flow temperature,  $T_3$ - $T_5$  are the refractory temperatures.

The set of experiments analyzed in the paper was carried out with the use of Kuznetsk bituminous coal (flame coal). Proximate and ultimate analysis of Kuznetsk bituminous coal (flame coal) and also particle size distribution of pulverized coal are presented in table 1.

**Table 1.** Proximate, ultimate analysis and particle size distribution of Kuznetsk bituminous coal.

Parameter	Technical and elemental composition										$Q_i$ , MJ/kg
	$W^a$ , %	$A^d$ , %	$V^d$ , %	$V^{daf}$ , %	$C^{daf}$ , %	$H^{daf}$ , %	$N^{daf}$ , %	$S^{daf}$ , %	$O^{daf}$ , %	$Q_i^{daf}$ , MJ/kg	
Laboratory values	2.9	23.7	29.9	39.2	78.8	5.97	2.16	0.97	12.1	31.6	21.6
Reference values	4.5	18	31.4	40.5	77.7	5.51	2.62	0.55	13.6	31.9	21.9
Particle size distribution											
Fraction, micron	160		100		80		71				< 71
Percentage, %	10.25		47.7		26		2				14

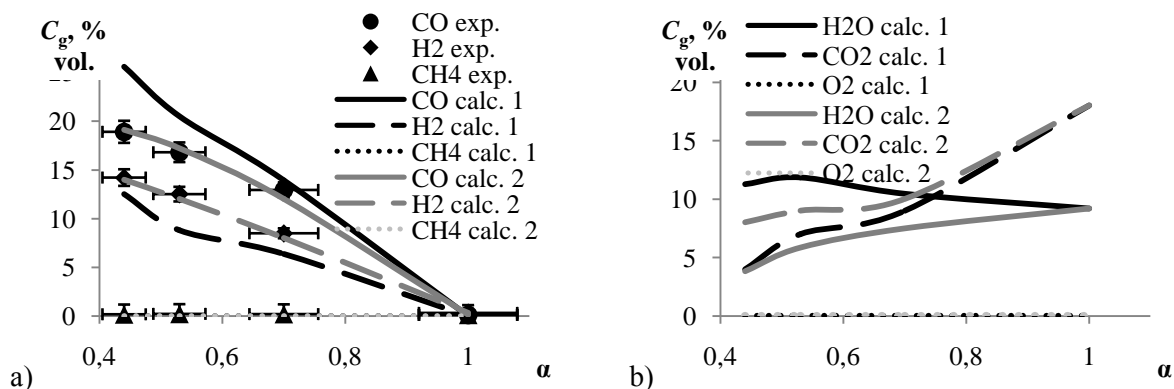
## 2.3. Experimental results

A set of air experiments (21% of oxygen) with  $\alpha$  (stoichiometric factor) = 0.44, 0.53, 0.7 and 1.01 (table 2) is considered in the paper. The coal mass flow was 5-15 kg/h, air flow rate was 20-60 Nm<sup>3</sup>/h. Pressure in the reaction chamber varied from 0.13 to 0.18 MPa, and blast temperature varied from 420 to 500°C, which corresponds to the compressed blast air temperature in the industrial air gasifiers.

**Table 2.** Experimental results of the air-blown coal gasification.

Parameter	Case 1	Case 2	Case 3	Case 4
Stoichiometric factor	0.44	0.53	0.71	1.01
Fuel consumption, kg/h	12.5	10.3	15	8.8
Air flow rate, Nm <sup>3</sup> /h	31.7	31.5	60.4	51.2
Flow temperature T <sub>1</sub> , °C	1095	1126	1291	1022
Brickwork temperature T <sub>2</sub> , °C	1155	1151	-	1124
Brickwork temperature T <sub>4</sub> , °C	994	987	1123	972
Air temperature, °C	493	502	451	421
Pressure P <sub>1</sub> , MPa	0.175	0.131	0.179	0.173
Synthesis gas composition, volume percent				
CO	18.9	16.8	12.9	0.1
H <sub>2</sub>	14.2	12.5	8.5	0.3
CH <sub>4</sub>	0.16	0.2	0.18	0.1
Lower heating value, MJ/m <sup>3</sup>	3.97	3.54	2.54	0.08

The experimental data processing was performed with the use of the rated equilibrium concentrations, defined by the entropy maximization method in the multiple-purpose software system Terra [5]. The rated equilibrium concentrations, presented in figure 3 have weakly nonlinear dependence on  $\alpha$ , due to different equilibrium mixture temperatures, which were taken to be equal to the experimental values of the flow temperature 1100-1300°C.



**Figure 3.** Experimental and calculated concentrations of the synthesis gas components in the gasifier: a) CO, H<sub>2</sub>, CH<sub>4</sub>; b) H<sub>2</sub>O, CO<sub>2</sub>, O<sub>2</sub>.

In the first calculation of the equilibrium concentrations, presented on the diagram, the unburned coal loss and the water gas shift reaction in the water quenching section were not considered. In the second calculation the reagents concentrations necessary for experimental synthesis gas compositions obtaining were defined. The rated unburned coal loss is approximately 10% at  $\alpha = 0.44$  and approximately 0% at  $\alpha = 1.01$ . The quantity of water reacted in the water quenching section exceeded three times the quantity of water in coal at  $\alpha = 0.44$ . In the complete combustion mode ( $\alpha = 1.01$ ) the water gas shift reaction had insignificant impact on the final synthesis gas composition due to no CO and H<sub>2</sub> in the combustion products.

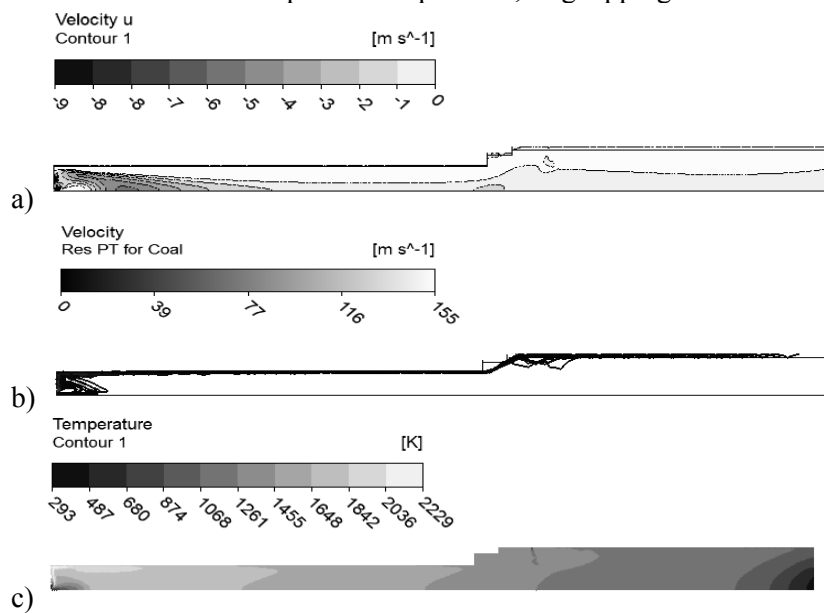
### 3. CFD model verification

The CFD model, described in [6] but with consideration of the project fuel kinetic constants (table 3), obtained by the TGA method was used for the analysis of the reverse flows, the pulverized coal fuel motion trajectories and the temperature fields in the chamber analysis. The Shear Stress Transport turbulence model was previously verified with the use of experimental data [7].

**Table 3.** Kinetic constants of heterogeneous reactions.

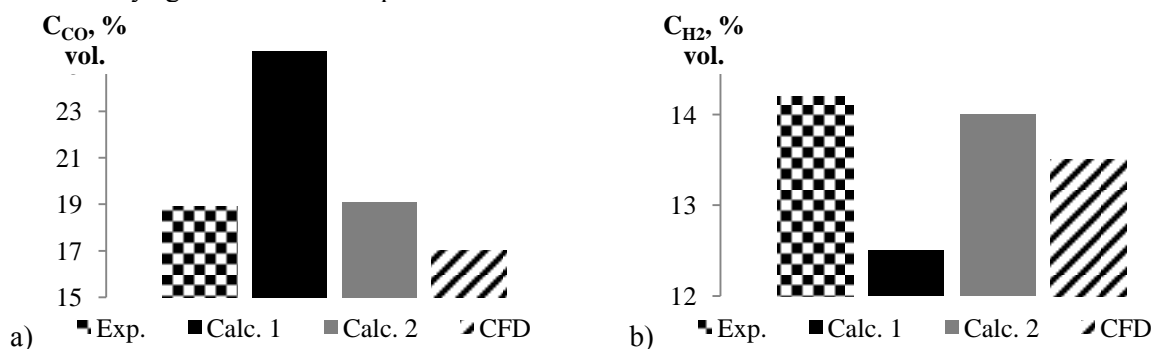
Constant	$C + O_2 = CO_2$	$C + H_2O = CO + H_2$	$C + CO_2 = 2 CO$
A, $kg/(m^2s)$	500	60000	40000
E, kJ/mol	70	160	170

The reverse flows are located in the near-axial zone of the chamber with the peak velocity values near the burner (figure 4a), which makes the process steady. It is seen from the calculated temperature field (figure 4b) that the pulverized coal is retained against the wall by the air twisted by the swirl burner therefore the flame core is located near the reaction chamber wall (figure 4c). The resultant cyclone effect leads to the particles separation, slag tapping and increasing range of the coal burnup.



**Figure 4.** The results of numerical simulation of the entrained-flow air gasification in the gasifier: a) reverse flows velocity (white color means the flow moving to the chamber outlet); b) the pulverized coal motion trajectories on the entrance region; c) temperatures distribution in the segment longitudinal cross section.

In this case  $CO$  and  $H_2$  concentrations in the synthesis gas at the outlet from the reaction chamber are the basic verification criteria (figure 5). The calculation results obtained by the CFD model are in satisfactory agreements with experimental data.



**Figure 5.** Comparison of  $CO$  (a) and  $H_2$  (b) concentrations, obtained during experiment, equilibrium calculations and CFD modeling.

#### 4. Gasifier development

The entrained-flow pressurized air gasifier development was performed with the use of the verified model. The two-stage fuel supply scheme (MHI type) was used due to the low TCP reaction rate in air. With the increase in the water vapor content in the working fluid the GTU efficiency is also increased. For hydrogen content increasing in the synthesis gas the vapor is added on the second gasifier stage and heat, necessary for the vapor gasification is compensated by supplementary heating of the blast air. It allows the gasifier chemical efficiency improvement, the increasing range of the coal burnup and hydrogen content increasing in the synthesis gas up to the required level. The gasifier slagging and pollutant emission impact is planned to be considered in future.

#### 5. Conclusion

- 1) Complex investigations are necessary to develop state-of-the-art entrained-flow air-blown gasifier for high-efficient IGCC. One of the most difficult issues is the gasifier TCP study. Combination of the experimental and CFD investigations are necessary to solve this problem.
- 2) Experimental study of gasification technology with initial data acquisition for CFD model verification was performed on the NPO CKTI gasifier. Syngas composition and temperature profiles inside the reactor at different stoichiometric ratio were analyzed. Hydrogen concentration raises and CO concentration decreases due to the water shift reaction in quenching section of gasifier. Unburned carbon level was up to 10%, which leads to combustible gases concentrations decrease.
- 3) Proposed CFD model consists of calibrate submodels and adjusted kinetic constants for heterogenic reaction that was obtained in TGA experiments. The model was verified with the experimental data and can be used for development of contemporary entrained-flow gasifier for high-efficient IGCC.
- 4) Two-stage air-blown MHI gasifier is proposed as prototype for further development. Modernization involves high temperature stream steam addition and blast air high-temperature heating.

#### Acknowledgements

This work was financially supported by the Russian Science Foundation (project no. 14-19-00524). We would like to express gratitude to Shestakov N.S, Shurchalin A.A. and the other staff of «NPO CKTI» JSC for their help in experiments within the framework of the presented project.

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